VII International Conference on Computational Methods in Marine Engineering
MARINE 2017
M. Visonneau, P. Queutey and D. Le Touzé (Eds)

APPLICATION OF 2D-WAVE SPECTRA TIME SERIES FOR PIPELAYING VESSEL STINGER STRUCTURAL ASSESSMENT

ANDREA DEL GUZZO*, FEDERICO GAGGIOTTI†, CRISTIAN ALBERTO ROSSETTI*, FRANCESCO SAVERIO DI TOMASO† AND ROBERTO BRUSCHI†

*SAIPEM S.p.A. Croatian Branch
Aldo Colonnello 2, 51000 Rijeka, Croatia
e-mail: Andrea.DelGuzzo@saipem.com,
CristianAlberto.Rossetti@saipem.com

†SAIPEM S.p.A.
Via Toniolo 1 61032 Fano (PU), Italy
e-mail: Federico.Gaggiotti@saipem.com, FrancescoSaverio.DiTomaso@saipem.com,
Roberto.Bruschi@Saipem.com

Key words: Stinger Design, 2D wave spectra

Abstract. In the recent years offshore oil and gas field development activities are moving towards deeper and more remote regions for which high performing installation spread is requested. In those conditions, the offshore pipeline installation in S-lay mode, that is generally preferred being more fast and efficient, presents many challenges in pipeline overbend section and requests a longer curved stinger section to support the pipeline weight during installation. The present paper is focused on stinger structure design and verification and describes the methodology followed to perform advanced global combined hydrodynamic and structural analysis through application of hindcasted 2D wave time series. The analysis is carried out in frequency domain, the vessel motion inducing stinger loads are calculated through application of vessel RAOs and a more realistic description of directional wave energy distribution through 2D sea spectra. Within the proposed methodology a more realistic estimation of dynamic forces vessel motion induced is achieved permitting an higher optimization in material utilization. The practical consequence is that the vessel operational limits can be extended but a more careful management of the offshore operation during execution phase is requested.

1 INTRODUCTION

In the recent years more and more offshore hydrocarbon reservoir have been discovered in challenging areas i.e. deeper locations characterised by harsher environmental condition. The field development includes the installation of infield flow lines and possibly the laying of long or very long export pipelines (sometimes also hundreds kilometres) to deliver the product from offshore to shore. Being faster and more efficient and then less expensive, the S-lay mode is generally preferred but, in those scenarios, presents many challenges in pipeline overbend section and requests a longer curved stinger section to support the pipeline weight during installation [2].

To extend the applicability of S-lay installation mode in deeper areas more performing vessel equipment is requested and particularly longer and lighter stinger ask for a highly optimized design.

In a challenging offshore market context where the contractor's investment for new assets is dropping, the request to explore the opportunity to employ the actual capability of the existing installation vessels towards more demanding scenarios, compared to the original design requirements, is also increasing. Currently many vessels equipped for S-Lay mode installation in relatively shallow water are available in the market and the request to investigate the possibility to modify the existing stinger structure making it suitable to the new and more demanding scenarios with minimum investment, as a part of the general system improvement, is becoming more and more frequent. For the above reasons advanced engineering analyses based on more controlled and less conservative approach is mandatory.

Nowadays no international standards provide specific guidelines for the structural design and verification of pipelaying stinger, therefore, robust and extensive engineering studies have to be performed, verified and accepted from the relevant certification bodies. First step for an optimized engineering design is to model realistically the main loads acting on the structure during its service life leaving to the successive structural analysis phase the possibility to reach the requested safety margin through conscious application of partial safety factors on loads and resistance characteristic design values (LRFD method [1]). Focusing on the stinger structure the main loads are coming from the pipeline sustained by rollers, and are primarily dependent on vessel motions [3],[4]. Direct hydrodynamic loads wave and current induced on the stinger in most of the cases can be neglected.

Regarding the simulated vessel behaviour on waves is well known that the real sea conditions generally induces a different vessel motions with respect to the one estimated during the design stage when seastate is theoretically described through synthetic parameter i.e. Significant wave height Hs, peak period Tp and incoming direction [5]. The main reason of this discrepancy must be researched on the classical sea state spectral parametrization including directional spreading formulation. For the range of Hs relevant for the pipelaying operation and considered for stinger design, which are generally significantly lower than survival extreme conditions, the synthetic sea parametrization is not able to fully describe the directional wave energy distribution.

The above is particularly true for the areas such as Offshore Brazil and West Africa where swell and wind sea are contemporarily present and coming from different directions. In those areas the typical representation of total sea brings to incorrect estimation of vessel motions [6].

Nowadays long hindcasting time series that can be considered representative of the waves conditions encountered in the area during the operation are available [7][8] and the more advanced numerical model can provide also a detailed directional distribution of the wave energy i.e. 2D spectra[9]. All these information can be utilized as input to simulate more realistically the vessel motions and the corresponding stinger induced loads.

As an example Figure 1 presents for a sea state of Hs=1.5m a comparison between theoretical and actual spectrum.

The directional distribution of the wave energy is quite different for the two cases and it is reflected in vessel motion estimation. Referring to a mono-hull pipelaying vessel, theoretical sea spectra induces higher vessel motions if compared with those corresponding to actual sea state. The vessel motions can be calculated in frequency domain through Response Amplitude Operators (RAOs) and the statistical maxima can be estimated and applied as input for the structural verification of the stinger structure. It is worth to underline that the present methodology for vessel motion estimation is general, and can be applied every time more rigorous vessel motion evaluation is requested. For the structural verification keeping as input the vessel motions calculated as above, it is still allowed to follow any recognised international standard or code check criteria without any particular constraint.

With proposed methodology a more consistent and effective factor of safety application is achieved resulting in safer and more optimized material utilization. In particular for the design of new stingers the final structure is safer, slender and lighter with positive impact on operational performances and on material and fabrication costs.

For stinger already in operation the new approach gives the opportunity to better assess the real capability of structure designed with different philosophy with possibility on extending its service life pushing toward more demanding scenarios e.g. deeper water of harsher areas.

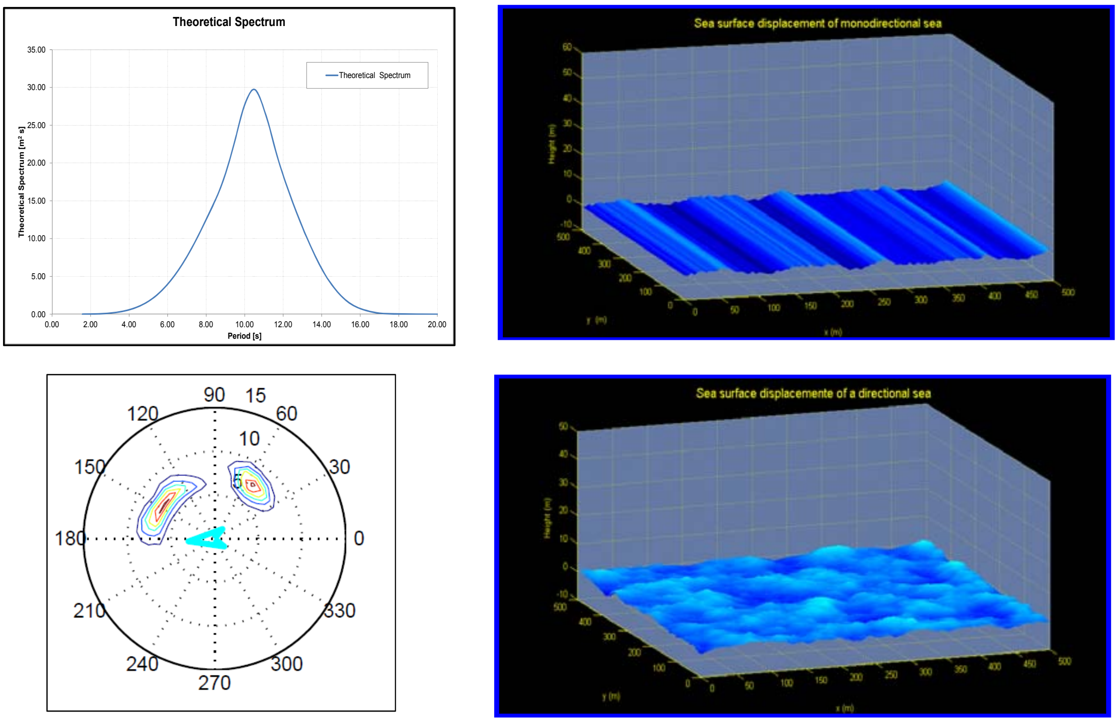


Figure 1: Comparison between theoretical monodirectional and actual sea spectrum for Hs=1.5m

The present paper is organized as follows. Section 2 provides the theoretical background on which the calculation is based. Section 3 describes how the general theory can be applied for the stinger structural analysis. Section 4 contains a typical example showing how the process can be a valuable way to perform global verification of an existing stinger structure confirming the possibility to extend the pipelaying water depth range towards deeper areas.

Discussion on the main outcomes and conclusions are collected in the last chapter.

2 THEORETICAL BACKGROUND

The structural verification of any offshore structure rigidly connected on a floating vessel e.g. FPSO topside or jacket transported on cargo barge is typically performed calculating statistical maximum of the vessel motions (displacement and acceleration) induced by 3 hours extreme design sea state. The extreme acceleration can be calculated through vessel Response Amplitude Operators (RAOs) that describe for each of the 6 Degree of Freedom (DOF- 3 translations and 3 rotations), for each frequency and for each vessel-wave relative direction how the vessel moves if excited by 1m amplitude regular wave.

The RAOs are generally provided in to the vessel Centre of Gravity (CoG) but can be transferred to any point under the hypothesis of rigid body motion. For a point with coordinates a, b, c with respect to CoG the translation is defined by:

$$\begin{cases} X_{abc}=X_{CoG}+c\theta_y-b\theta_z \\ Y_{abc}=Y_{CoG}-c\theta_x+a\theta_z \\ Z_{abc}=Z_{CoG}+b\theta_x-a\theta_y \end{cases} \tag{1}$$

where $\theta_x, \theta_y, \theta_z$ are the rotation angles around the three coordinates axes. Therefore, given the motion RAOs at the CoG defined as:

$$\underline{X}_{CoG}=\underline{X}(\omega,\theta)\cdot e^{i(\omega t+\phi)} \tag{2}$$

the motion, velocity and acceleration RAOs for each of the 6 DOF at any generic point can be calculated as:

$$\underline{X}_{abc}=\underline{X}_{abc}(\omega,\theta)\cdot e^{i(\omega t+\phi)} \tag{3}$$

$$\underline{\dot{X}}_{abc}=i\omega\underline{X}_{abc}(\omega,\theta)\cdot e^{i(\omega t+\phi)} \tag{4}$$

$$\underline{\ddot{X}}_{abc}=-\omega^2\underline{X}_{abc}(\omega,\theta)\cdot e^{i(\omega t+\phi)}=(\ddot{X}_{abc}, \ddot{Y}_{abc}, \ddot{Z}_{abc}) \tag{5}$$

The acting force in vector form $\underline{F_i}$ on i-th beam-like body positioned at coordinates a,b,c with respect to CoG can be defined:

$$\underline{F_{Dyn,i}} = m_i \underline{\ddot{X}}_{abc} + \rho V Ca(\underline{\ddot{X}}_{abc} - \underline{\ddot{U}}_{abc}) + \frac{1}{2}\rho Cd Ai(\underline{\dot{X}}_{abc} - \underline{\dot{U}}_{abc}) \,|\, \underline{\dot{X}}_{abc} - \underline{\dot{U}}_{abc} \,| \tag{6}$$

Where:

$\underline{F}_{Dyn\,i}$ = force applied to the beam-like element (normal to the beam axis);

m_i = structural mass;

ρ =water density

V=displaced volume

A_i = cross area of the beam-like body;

C_a = added mass coefficient;

C_d = drag coefficient;

$\underline{\dot{X}}_{abc}$ = velocity of the beam-like body (normal to the beam axis);

$\underline{\dot{U}}_{abc}$ = velocity of the water particle (normal to the beam axis);

$\underline{\ddot{X}}_{abc}$ = acceleration of a beam like object (normal to the beam axis);

$\ddot{\underline{U}}_{abc}$ = acceleration of water particle (normal to the beam axis).

The loads calculated as per the above formulation are applied, and the equilibrium and compatibility equations are solved for each frequency. The transfer functions of the force (FAO) for each i-th beam element are then obtained as shown in figure 2.

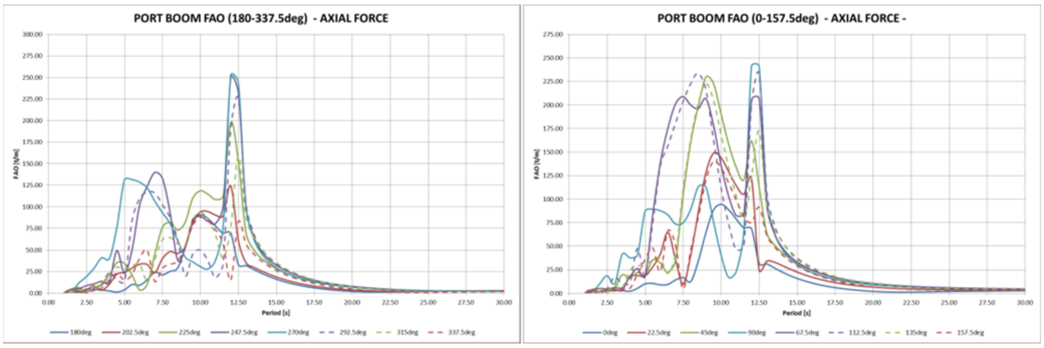


Figure 2: Force Amplitude operator (FAO) – Axial - for direction 0-360deg.

Figure 2 presents the FAO for the axial forces acting on a structural member along his axis. The FAO and the sea state spectra can then be combined to calculate the force spectrum.

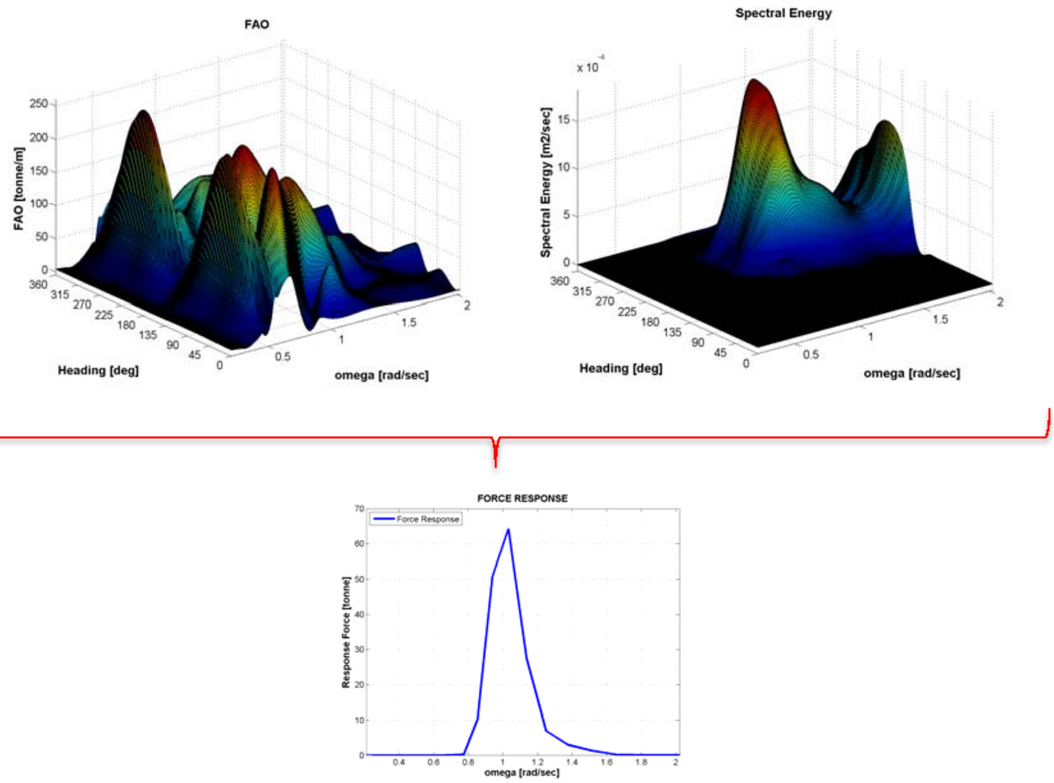


Figure 3: Axial force spectrum in a structural member as a function of a directional wave spectrum

As an example Figure 3 shows how can be calculated the axial dynamic load $F(\omega, \vartheta)$ induced by vessel motion on a structure specific location. It represent a graphical schematization of the Eq. (7) and (8) for a specific wave spectrum.

$$S_F(\omega,\theta)=[F(\omega,\theta)]^2\cdot S_{\eta\eta}(\omega,\theta) \tag{7}$$

$$F_{sig}=2\sqrt{\int_0^{+\infty}\int_0^{2\pi} S_Z(\omega,\theta)d\omega\, d\theta}=2\sqrt{m_0} \tag{8}$$

The statistical expected most probable maximum dynamic force is calculated for N hours sea state following Rayleigh statistic formulation:

$$F_{extr,mean}=F_{sig}\,\frac{1}{\sqrt{2}}\left\{\sqrt{\ln\left(\frac{N*3600}{T_z}\right)}+\frac{0.2886}{\ln\left(\frac{N*3600}{T_z}\right)}\right\}\cdot CF \tag{10}$$

$$F_{extr,mode}=F_{sig}\,\frac{1}{\sqrt{2}}\left\{\sqrt{\ln\left(\frac{N*3600}{T_z}\right)}\right\}\cdot CF \tag{11}$$

where the zero up-crossing period T_z the band width correction factor CF, the ε^2 spectrum broadness parameter and m_n the even moments of the spectrum, are:

$$T_z=\sqrt{\frac{m_0}{m_2}} \tag{12}$$

$$CF=\sqrt{1-\varepsilon^2} \tag{13}$$

$$\varepsilon^2=\frac{m_o m_4-m_2{}^2}{m_o m_4} \tag{14}$$

$$m_n=\int_0^{+\infty}\int_0^{2\pi}\omega^n S_F(\omega,\theta)d\omega d\theta \tag{15}$$

As per Eq. (8), the total significant force is calculated as the result of a double integration on the frequencies and directions. The final force acting on the stinger is calculated adding the static (load for zero environments) and dynamic component:

$$F_{Max}=F_{extr,mode}+F_{Stat} \tag{16}$$

3 CASE STUDY: VERIFICATION OF EXISTING STINGER STRUCTURE

The above methodology has been applied to verify the suitability of an existing stinger structure, initially designed for S-lay operation in relatively shallow water areas, on laying in deeper areas with harsher environment. The laying scenario refers to 14” pipe installation in 500m water depth.

The stinger is composed by 2 rigid ramps (from now on referred as truss and intermediate), and a floating section connected to intermediate. Stinger ramps have 3 rollers on the truss section, 1 roller on the intermediate section and 4 rollers on floating ramp. All the stinger sections are reticular structures and connected to a laying barge 120m length and 33m wide for which the main characteristics and operative laying loading conditions are listed in Table 1.

Table 1: Laying barge main characteristics

Floating Position	Displacement	21815.0	[tonne]
	Draft At AP	6.52	[m]
	Draft At Midship	5.94	[m]
	Draft At FP	5.36	[m]
	KMT	16.28	[m]
	KG	9.44	[m]
Natural Periods	Heave, $T_{n,3}$	8.4	[s]
	Roll, $T_{n,4}$	11.7	[s]
	Pitch, $T_{n,5}$	8.0	[s]

3.1 Numerical model

The dynamic load induced by the pipeline during laying operation has been applied as static forces acting on the roller locations. On the fixed ramps the maximum expected dynamic forces on rollers are applied assuming that the maximum loads on the stinger due to pipeline occur at the same instant. On the floating ramp, to properly reproduce the behavior during operation, only pipeline's static loads have been considered.

The mass and buoyancy are correctly reproduced through combined structural and hydrodynamic model. For this latter the hydrodynamic forces on slender element has been estimated applying Morison theory and for large volume element, like barge, through potential panel method. The stinger is connected to the laying barge through:

- Lower connection: hinge allowing only rotation on the vertical plane;
- Upper connection: boom braces hinged both side to barge and stinger allowing only rotation around hinge axes.

Boundary conditions applied in the model are chosen to properly reproduce the transfer of forces between elements. Pinned connections are applied on the upper and lower hinges on the vessel and for the connection between the intermediate and the floating ramp. For the numerical calculation purposes only, in particular to make the structure properly constrained, an extra support is requested to the floating ramp tip. For each analysis the ballast water in the floating ramp has been defined to assure in each laying scenario a negligible reaction on the tip support. Figure 4 presents the combined structural/hydrodynamic model of the stinger and the boundary conditions applied.

For the hydrodynamic model the stinger structure has been modeled through tubular sections and rollers supporting pipelines are included, so that correct weight and drag is modeled. For both elements, tubular section and rollers, the applied drag and added mass coefficient are C_D =0.8 and C_A=1.0 respectively.

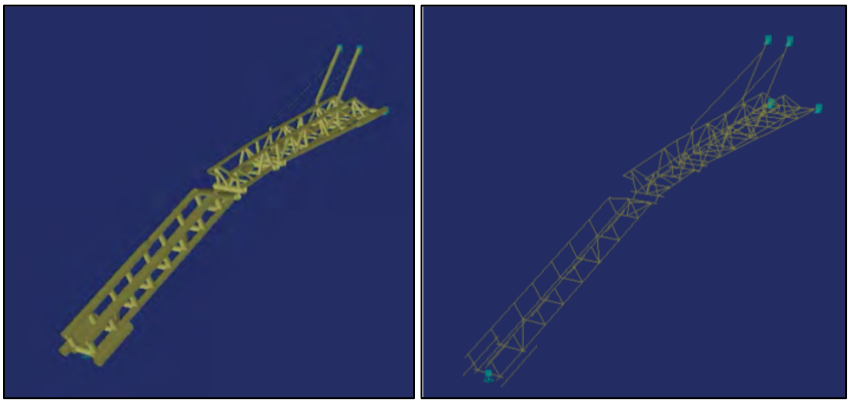


Figure 4: Stinger model and model boundary conditions

The analysis has been performed through SESAM (DNV) suite [10], in particular GeniE, WADAM, SESTRA and Xtract packages have been used for design of the structure, Hydrodynamic loads calculation, for structural analysis and results post-processing, respectively.

The combined analysis with barge and stinger model has been performed to calculate the FAO. For the specific case, only FAOs from 0 to 360 deg with a step of 22.5 deg and 0.5s of resolution for the jacking booms have been calculated. A dedicated analysis has been performed to clearly identify the structural element that in a hierarchical scale for all the loading conditions is the first reaching the structural limit. In this way a clear and well defined criterion has been identified and corresponds to the maximum structural capacity of jacking boom elements.

All the 2D wave spectra, 50 years long time series of 3 hours sea state, for the representative laying scenario has been applied. The forces induced by vessel motions on the booms are computed considering the relative angle between vessel and incoming wave direction assuming, for each section of the pipe to be laid, the realistic vessel heading.

It is worth to note that for the case where a unique screening criterion cannot be identified the described methodology is still applicable but the calculation has to be repeated for all possible limiting conditions e.g. structural integrity for various structural elements or nodes.

The calculation effort will increase and final acceptable sea states are those that contemporarily satisfy all possible limiting criteria.

3.2 Case study results

Making reference to the model described above for all the events in the time series the forces on jacking booms have been calculated. The loads from pipeline statically applied to the stinger in rollers location for the analyzed scenario are given in Table 2. The limiting force for the jacking booms is assumed to be 400t each. In Figure 5, the stinger starboard and portside jacking booms FAOs for the analyzed laying scenario are shown.

Table 2: Pipe loads on stinger system rollers-rollers numbering from vessel barge hinges.

CASE	CRITERIA CHECK	Stinger			Intermediate	Floating			
		TR1	TR2	TR3	I1	SR1	SR2	SR3	SR4
[-]		[t]	[t]	[t]	[t]	[t]	[t]	[t]	[t]
Normal Lay scenario 500m WD	Static	36.5	10.5	38.5	10.9	29.9	19.2	13.9	0.0
	Dynamic	41.0	14.7	49.6	33.0	46.0	28.1	32.7	8.5
	Total	**77.5**	**25.2**	**88.1**	**43.9**	**75.9**	**47.3**	**46.6**	**8.5**

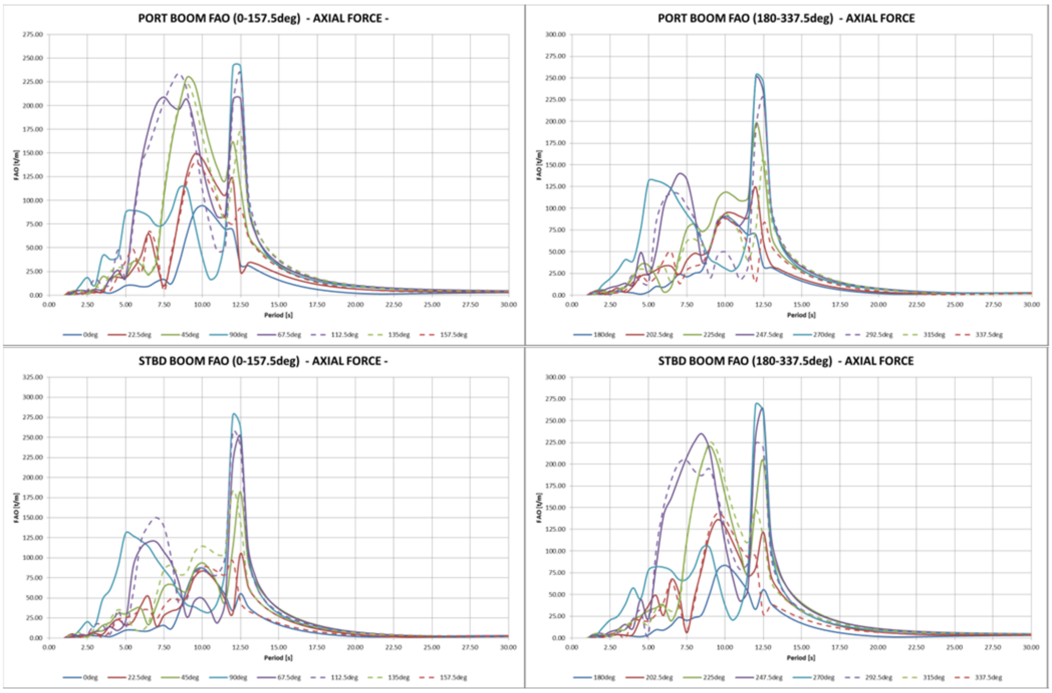
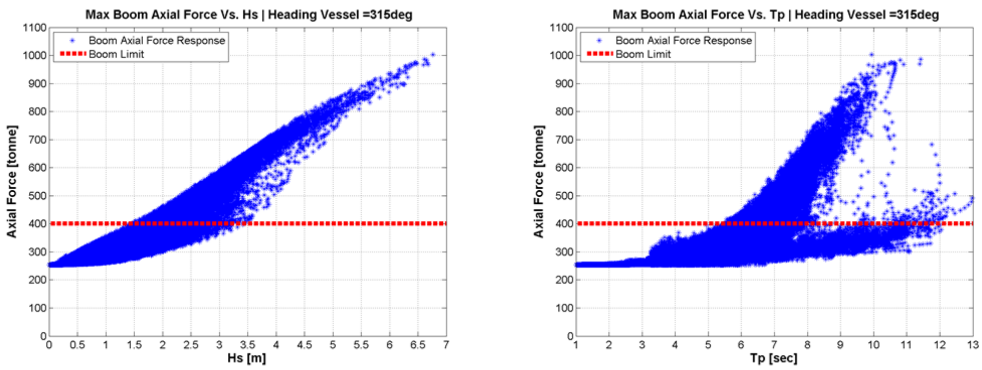


Figure 5: Force Amplitude Operator of axial force for Starboard and Portside jacking boom

Appling the FAO and all the 2D spectra sea state in the 50 year long time series the axial forces on the booms are calculated. The resulting axial loads are plotted against the Hs, Tp, spreading and relative direction (Figure 6).



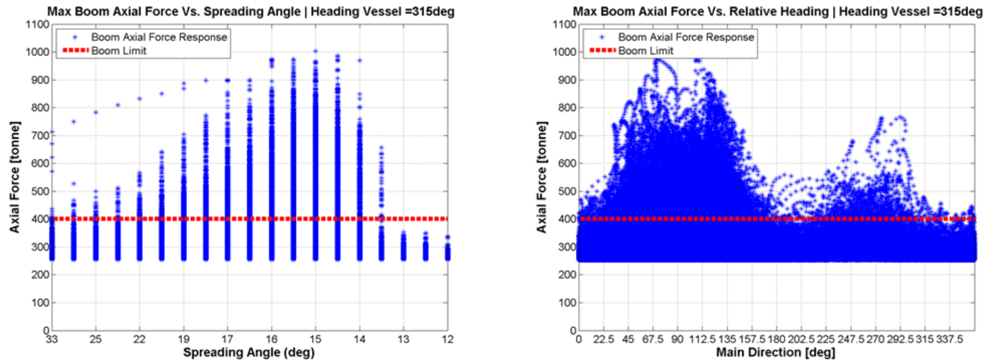


Figure 6: Starboard and Portside axial loads on stinger jacking booms Vs Hs, Tp, Spreading and relative wave incoming direction for 50 years hindcasted 2D time series.

Referring to the installation scenario of laying 14” pipeline in 500m water depth to evaluate the improvement in terms of installation performances, the same stinger structural assessment has been repeated considering the sea states time series provided in term of synthetic parameter Hs, Tp and regular wave approach (H_{max}=H_{reg}=Hs*1.83). In the standard approaches a long-crested sea or regular wave no directional distribution of the sea state energy, is accounted for. Comparing the results of the proposed methodology with the standard ones i.e. regular and irregular wave approaches the improvement in terms of stinger performance can be evaluated.

Figure 7 presents the axial loads on booms calculated for the considered methodologies.

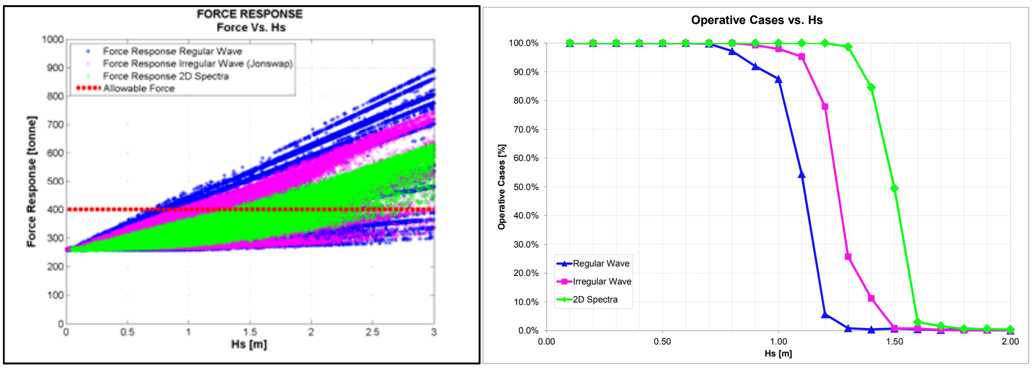


Figure 7: comparison between axial boom force from fully 2D spectra, synthetic parameter and regular wave approach

Referring to the Hs for the considered laying scenario, assuming acceptable an operative limit not smaller than 65% is observed that a sea state of Hs of 1.46m can be assumed as upper limit. For the same Hs the classical approach, based on synthetic parameter Hs/Tp, gives around 5% operability, too low to be considered acceptable. Same if regular wave approach would be applied. With the improved methodology 60% of actual operative cases that with the classical approaches resulted not operative are then included. In other words the overall operability increase achieved with the applied methodology is around 60%.

Regarding the allowable sea states Hs≤1.0m result operative cases independently on the verification methodology applied. Hs ≥1.2m and Hs ≥1.1m are never acceptable if irregular or regular wave approach is respectively considered. From the analysis with 2D spectra comes that for Hs up to 1.46m the stinger structure is not a limiting factor.

For the specific laying scenario the limit of the installation spread is Hs ranging between 1.4m and 1.5m. So Hs=1.45m can be reasonably assumed as the overall limit for the laying operation.

Focusing the attention only to the stinger structure, accepting a reduced operability, also higher limits can be considered acceptable but in this case under certain conditions.

In pipelaying installation it can be acceptable for short weather windows operations such as initiation or final laydown but not for normal laying during long laying campaign for which low operability corresponds to unacceptable cost and operational risk increase due to long waiting on weather and increase of number of pipe abandonment and recovery operations.

Considering acceptable an operative level of 40% the new approach allows including sea states with Hs up to 1.55m. For the same Hs the regular and irregular wave approaches gives 16% and 26% lower Hs limits.

Within the 2D spectra approach the limits are increased since also during the engineering study phase the dependence of vessel motion on wave height, peak period, and directional energy distribution can be properly account. The same is not possible in case classical regular and irregular wave based methodologies are applied.

From the above a more careful management during execution phase is requested and specific operational procedures, reliable and high quality weather service forecast during installation execution are needed.

4 CONCLUSIONS

The present paper presents and describes new methodology to be applied to verify the stinger structure capability accounting for a more realistic description of sea state. The methodology is general and can provide an appreciable benefit for all the cases when floating structures and floating structure's equipment design loads are mainly related to dynamic motions.

The method is based on the proven assumption that the classical way to describe the sea state through synthetic parameter Hs and Tp, inducing vessel motions, in most of cases barely reproduce the realistic sea condition. This is particularly true for area such as West Africa or Brazil affected by crossed sea state i.e. Wind Sea and Swell contemporary present. The consequence is that extreme vessel motions considered for equipment designed and calculated during design phase are overestimated with respect to actual on board registration.

Nowadays state of art hindcasting numerical models are able to provide a detailed and more realistic description of the sea state including a more realistic directional distribution of wave energy. The frequency domain analysis based on the 2D sea spectra time series allows a better estimation of the main loads for the vessel motion.

The proposed methodology bring an improvement of the design load estimation without any variation on the next structural design phase. The design approach and corresponding verification criteria as per most appropriate international standard can still be followed.

For the present paper the general methodology accounting for hindcasting sea state 2D spectra has been applied for the structural verification of stinger already in operation. The aim was to demonstrate that the structure can be suitable for the installation on more demanding scenarios comparing to those initially accounted for the original design.

A practical example has been provided showing a significant improvement of around 60%

in term of pipe laying operability. The methodology can be followed to optimize the design of new build stinger allowing more slender, light and definitively more performing structure.

The real benefits are in material and fabrication costs with additional saving on management and system maintenance during service life.

REFERENCES

[1] DNV Os-C-101, April 2011, Design of Offshore Steel Structures, General (LHRF method)

[2] Bruschi R., Vitali L., Marchionni L., Parrella A., Mancini A. Pipe technology and installation equipment for frontier deep water projects. *Ocean Engineering* (2015) 108:369–392.

[3] Xiangfeng Zhang, Qianjin Yue and Wenshou Zhang, The Model Test of Deep Water S-Lay Stinger Using Dynamical Substructure Method, *Journal of Offshore Mechanics and Arctic Engineering* (2015) 137(1): 011701-011701-8.

[4] Wang, L., Zhang, X. F., Lv, W., Yue, Q. J., He, N., and Zhou, L. Conceptual Analysis of Stinger for Ultra-Deepwater S-Lay, *3rd International Deep-Ocean Technology Symposium ISOPE* (2009), Beijing, China, 55–81.

[5] van Dijk RT, Quiniou-Ramus V, Le-Marechal G., Comparison of Full-Scale Measurements With Calculated Motion Characteristics of a West of Africa FPSO. , *Proc 22nd Int Conf on Offshore Mechanics and Arctic Engineering OMAE* (2003) Volume 1 Offshore Technology; Ocean Space Utilization, Cancun, Mexico, 335-339.

[6] Drago M., Del Guzzo A., Vitali L., Bruschi R., Assessment of Expected Weather Stand-by for Off-Shore Operations with Motion Limit Criteria *Proc 27th Int Offshore and Polar Eng Conf, San Francisco, ISOPE* (2017).

[7] Cox A, Swail V A global wave hindcast over the period 1958-1997: Validation and climate assessment. *J Geophys Res* (2001) 106: 2313–2329.

[8] Soares C,Weisse R, Carretero J, Alvarez E A 40 years hindcast of wind, sea level and waves in European waters , *Proc. 21st Int Conf on Offshore Mechanics and Arctic Eng*, *Norway, Oslo*, OMAE (2002).

[9] Graham, C., V.J. Cardone, E.A. Ceccacci, M.J. Parsons, C. Cooper and J. Stear. Challenges to Wave Hindcasting in the Caspian Sea, *7th International Workshop on Wave Hindcasting and Forecasting*, Banff, Alberta, Canada (2002).

[10] SESAM (DNV) User Manual October 7th 2016.